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**MATERIAL REQUIREMENT AND DESIGN CRITERIA
FOR PREVENTING BRITTLE FRACTURE IN
NODULAR CAST IRON SPENT
FUEL SHIPPING CONTAINERS**

Report No 84-376-K

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ABSTRACT

A preliminary material requirement and design criteria for using nodular cast iron in irradiated fuel management are presented. The purpose of this work was to review the material properties and design criteria which are relevant to the fracture prevention of nodular cast iron shipping containers. A series of fracture mechanics analyses were performed to demonstrate the interaction between design stress, flaw size and critical fracture toughness. Future work that will be required to qualify cast iron shipping containers for Canadian use has been recommended.

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EXECUTIVE SUMMARY

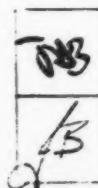
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This report presents the material requirement and design criteria for preventing brittle fracture in nodular cast iron spent fuel shipping containers. The purpose of this work was to review the material properties and design criteria which are relevant to the fracture prevention of nodular cast iron shipping containers.

In this report, a series of fracture mechanics analyses were performed to provide a quantitative basis for assessing the margin of safety inherent to a particular cask. It was demonstrated through a linear elastic fracture mechanics (LEFM) procedure that a proposed shipping cask design, of the candidate nodular cast iron material, can withstand a nine-meter drop test. No crack initiation would occur even if a flaw of a size well above the detection limit of conventional nondestructive examination existed in the cask. The fracture toughness of nodular cast iron is sufficient to ensure the structural integrity of these casks.

Future work that will be required to qualify cast iron shipping containers for Canadian use has been recommended.



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**MATERIAL REQUIREMENT AND DESIGN CRITERIA FOR
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B. Mukherjee and Y.J. Kim

1.0 INTRODUCTION

1.1 Objectives

This report documents a preliminary analytical assessment carried out on the proposed Irradiated Fuel Transportation Casks constructed of nodular (ductile) cast iron, to determine their material requirement and design criteria for preventing brittle fracture under hypothetical accident conditions. These conditions include a 9 m (30 ft) drop onto an unyielding surface in the worst configuration. This work is in support of the Nuclear Materials Management Department's (NMMD) Transportation Cask development project.

The objectives of this report were to review the material properties and design criteria which are relevant to the fracture prevention of nodular cast iron shipping containers. A series of fracture mechanics analyses were performed to demonstrate the interaction between design stress, flaw size and critical fracture toughness. Future work that will be required to qualify cast iron shipping containers for Canadian use has been recommended.

1.2 Background

A number of large nodular cast iron casks weighing more than 100 tonnes have been built, tested, licensed and introduced into service in a storage/transportation capacity/1,2/. In order to demonstrate the immunity of the spent fuel containers from brittle fracture under accident conditions several drop tests with a 1/3 model at room temperature and at -40°C were performed successfully. One test was done where an artificial notch having a depth of 1/3 wall thickness was introduced in the area of maximum stress. No cracks were found after the test (temperature of this test is not given in the paper)/3/. In another demonstration test a full scale cask weighing

about 100 tonnes was subjected to simulated aircraft impact tests. The projectile impacted in the middle of the wall with the cask standing upright. The impact resulted in a deformation of cooling fins in an area limited to the impact area. No cracks were found in the casting (again the temperature of this test is not given in the paper)/2/.

In the USA, The Virginia Electric & Power Company has agreed to purchase a Castor V dry storage cask from Gesellschaft Fuer Nuklear-Services (GNS) for its spent fuel dry storage demonstration project/4/.

In Ontario Hydro, the NMMD assessed the economical and technical feasibility of using cast iron cask/canisters in irradiated fuel management/5/. It was concluded that there is sufficient potential to warrant further investigation into the use of cast iron as a material for a reusable transportation cask or a simple storage canister.

Two cask designs were proposed by the NMMD. A smaller road cask which can accommodate two fuel modules (196 fuel bundles) and a larger rail cask which can accommodate six fuel modules (576 fuel bundles). Figure 1 shows the schematic drawing of the road cask. The cask is essentially a tightly sealed vessel with a 25.4 cm (10 inch) steel wall. The fuel is "top loaded" into the cask body, and a lid is bolted on. The containment boundary comprises the cask body, the body-to-lid seals, and the seals and components of two valve penetrations. The approximate size of the road cask is 1.85 m (length) x 1.5 m (width) x 2.1 m (height) while the size of the rail cask is 1.85 m (width) x 1.5 m (width) x 4.2 m (height). The mass of the loaded cask is approximately 30 tonnes for the road cask and 67 tonnes for the rail cask, respectively.

2.0 DESIGN CRITERIA FOR NODULAR CAST IRON SHIPPING CONTAINERS

Schwartz and Boyce/6/ have established a design criteria for cast iron shipping containers for the US Nuclear Regulatory Commission. These criteria are reviewed briefly in this section. Other options which are available for the design of a shipping container for Canadian use are also indicated.

2.1 Design Criteria For Preventing Ductile Failure

The design criteria for preventing ductile failure is based on the ASME Boiler and Pressure Vessel Code, Section III. Specifically, the values of design stress intensities (S_m) for nodular cast iron should be the lesser of the 1/4 minimum ultimate tensile strength (S_u), or 1/2 of the minimum yield strength (S_y).

Under normal conditions, the value of the stress intensity resulting from the primary membrane stress should be less than the design stress

intensity, S_m and the stress intensity resulting from the sum of the primary membrane stresses and the primary bending stresses should be less than $1.5 S_m$. In an accident condition, the stress intensity resulting from the primary membrane stresses should be less than the lesser value of $2.4 S_m$ or $0.5 S_u$. Also, the stress intensity resulting from the sum of the primary and secondary membrane stresses should be the lesser of $3.6 S_m$ or $0.75 S_u$.

Design criteria to prevent fatigue failure is also established in /6/. However, fatigue is not a major consideration for the shipping containers.

2.1.1 Minimum Material Properties for Ductile Fracture Prevention

It should be recognized that an American standard (ASTM or ASME) for nodular cast iron, applicable to thick section spent fuel shipping containers does not exist. The German standard for nodular cast iron is limited to castings with a wall thickness of less than 200 mm. For wall thickness greater than 200 mm, material acceptance criteria must be agreed upon between the casting manufacturer and the client. In view of the licensing requirement, it may be necessary to get such data accepted by the licensing authority.

2.2 Design Criteria for Preventing Brittle Fracture

The fracture arrest principle and the fracture initiation principle, have been applied in the design consideration for preventing brittle fracture of shipping containers.

2.2.1 Fracture Arrest Criteria

The toughness measure used in this method is the nil ductility transition temperature (NDTT). The material for a cask is selected with a sufficiently low NDTT so that the material is on the upper shelf of its fracture transition curve at the lowest service temperature. The usefulness of the NDTT for nodular cast iron is limited since there is no recognized method of measuring NDTT in this material. The estimated NDTT values show large scatter and are higher than those in ferritic steel. Nodular cast iron does not reach the upper shelf of its fracture transition curve at the lowest service temperature.

2.2.2 Fracture Initiation Criteria

The prevention of brittle fracture using fracture initiation criteria involves limiting the combination of stress level and flaw size below the critical fracture toughness of the material. In this approach the allowable flaw sizes and flaw inspection requirements are determined from the design stress values and the lower bound dynamic fracture

toughness of the material at the lowest operating temperature. The brittle fracture resistance of a prototype shipping cask is demonstrated on the basis of drop tests of unflawed full size or subsized casks.

This approach may be used to qualify a nodular cast iron shipping container for Ontario Hydro's use provided a suitable lower bound dynamic fracture toughness curve is established as a function of temperature. The dynamic fracture toughness tests should meet the criteria of ASTM E-399, Test for Plane-Strain Fracture Toughness of Metallic Materials. Other test methods such as crack arrest tests, dynamic J-integral tests and dynamic precracked Charpy tests may also be used to add to the dynamic fracture toughness data.

2.3 Determination of Brittle Fracture Acceptance Criteria From Drop Tests

Due to the paucity of 'ASTM valid' dynamic fracture toughness data, the current recommendation to US NRC is to establish the maximum allowable flaw size for nodular cast iron shipping casks by drop testing (free drop and puncture tests) full size casks with artificial flaws/7/. Flaws are introduced in the casting at locations where maximum tensile stress levels are expected, and with an orientation that is normal to the direction of the stress. The sizes and shapes of the flaws are optional, keeping in mind that the adopted flaw size will establish inspection requirements. After the drop tests the flaw should not propagate more than 3/4 of the way through the wall at locations of secondary stress gradients. The flaw should also not 'initiate' (extension less than 3.2 mm) at primary membrane or bending locations.

The maximum allowable flaw size for a production nodular cast iron shipping cask is $a_c/6$, where:

$$a_c = a_T \left(\frac{K_{ID(min)}}{K_{ID(flav)}} \right)^2$$

and a_c = minimum quasi-critical flaw size

a_T = size of the test flaw

$K_{ID(flav)}$ = dynamic fracture toughness at the site of the test flaw.

$K_{ID(min)}$ = minimum dynamic fracture toughness derived from samples taken from various locations in the prototype casting.

The recommended method for measuring K_{ID} in qualifying it for acceptance is the pre-cracked Charpy impact test. The maximum allowable flaw size, in any case, should not be less than 10 mm deep.

3.0 SUMMARY OF MATERIAL DATA

The ductility of cast iron can be significantly improved by adding inoculants such as magnesium to produce a uniform dispersion of free graphite in the form of spherical particles, called nodules. Nodular cast iron is essentially free of other forms of graphite. Maximum ductility is achieved when the nodules are embedded in a ferrite matrix. A fully ferritic microstructure can be obtained only by heat treatment. As cast, ductile cast iron contains some pearlite. It increases the iron's strength and hardness at the expense of lower ductility. A number of grades of nodular cast iron are produced, covering a range of ferrite/pearlite ratios.

Specifications for nodular cast iron are provided by the American Society for Testing and Materials (ASTM) under ASTM A-536 and A-395 as shown in Table 1. The three numbers in the grade designation refer to the ultimate tensile strength (S_u) the yield strength (S_y) and 0.2% elongation (ϵ), respectively. The specifications for nodular cast iron in the Federal Republic of Germany are DIN-1693. Its five grades shown in Table 2, roughly parallel those of ASTM A-536. The Grades GGG-40 and GGG-40.3 are the German designation for a ferritic nodular cast iron and have been used for the fabrication of cast iron shipping containers.

TABLE 1 ASTM A-536 GRADES OF NODULAR CAST IRON

Grade	Ultimate Tensile Strength (S_u) (MPa)	Yield Strength (S_y) (MPa)	Elongation (ϵ) (%)	Matrix
60-40-18	414	276	18	Ferritic
65-45-12	448	310	12	Ferritic/ Pearlitic
80-55-06	552	379	6	Pearlitic/ Ferritic
100-70-03	689	683	3	Pearlitic
120-90-02	827	621	2	Tempered Martensitic

TABLE 2 DIN-1693 (FEDERAL REPUBLIC OF GERMANY)
GRADES OF NODULAR CAST IRON

Grade	Ultimate Tensile Strength (S_u) (MPa)	Yield Strength (S_y) (MPa)	Elongation (ϵ) (%)	Matrix
GGG-40	400	250	15	Ferritic
GGG-40.3	400	250	18	Ferritic
GGG-50	500	320	7	Pearlitic/ Ferritic
GGG-60	600	380	3	Pearlitic
GGG-70	700	440	2	Pearlitic
GGG-80	800	500	2	Tempered Martensitic

3.1 Fracture Properties of Heavy Section Nodular Cast Iron

Information on fracture toughness properties of heavy section cast iron that is used for transportation casks is sparse. A co-operative test program was conducted in West Germany by the manufacturers and the users of transportation casks to investigate the fatigue and fracture properties of GGG-40 in heavy sections/8/. Approximately 600 and 700 mm thick test blocks were cast. An induction furnace was used for melting. Innoculation with magnesium was carried out immediately before casting the test blocks and the pouring temperature was kept in the range of 1300 and 1350°C. Additional mould inoculation was also carried out.

The notched impact energy (Charpy) values as a function of temperature are reproduced from Reference/8/ in Figure 2. 100, 150 and 200mm thick notched and pre-cracked compact tension specimens were used to measure fracture toughness values at temperatures between -140°C and 20°C. Plane strain fracture toughness (K_{IC}) values were obtained from those specimens which showed a valid test response according to the ASTM E-399 test criteria. An estimate of linear elastic fracture toughness K_0 was obtained from those specimens which showed an elastic-plastic behaviour. Toughness values at maximum load K_{max} were also determined. The fracture toughness values of GGG-40 (K_{IC} , K_0 and K_{max}) are shown in Figure 3 as a function of temperature. It shows that below -60°C the fracture behaviour of the material is brittle. The minimum K_{IC} values are 30 MPa $\sqrt{m}$ at -140°C and 45 MPa $\sqrt{m}$ at -60°C. Above -60°C, the behaviour of the material is increasingly elastic-plastic. Valid K_{IC} values were not obtained even with the 200 mm thick specimens. Only K_0 and K_{max} values are obtainable above -60°C. K_0 values increase with temperature to approximately 100 MPa $\sqrt{m}$ at 20°C.

Critical crack opening displacements were also measured in some of these tests. The crack opening displacement (COD) versus temperature behaviour (Figure 4) were similar to the toughness versus temperature behaviour for this material.

3.2 Fracture Toughness of Spent Fuel Casks

A limited amount of fracture toughness tests were conducted using test material from the midsection of a 438.5 mm thick wall of a Caster Ia spent fuel cask/9/. The particular cask from which the test material was taken had been subjected to a series of nine-meter drop tests. There was no significant damage to the cask as a result of these tests and no cracks were observed in the cask body. Two 100 mm thick notched and pre-cracked compact tension specimens were tested at -40°C using static and rapid (maximum load reached in 20 to 30 milliseconds) loading rates. The specimens did not fail by cleavage fracture. The load-displacement trace exhibited an initial linear behaviour followed by plastic deformation and/or stable crack growth. The K_{I0} values were approximately $56 \text{ MPa}\sqrt{\text{m}}$ for the static loading and $50 \text{ MPa}\sqrt{\text{m}}$ for rapid loading rates. Equivalent static K_{IC} values from J-integral tests of 25 mm thick compact tension specimens at -40°C ranged from 51 to 59 $\text{MPa}\sqrt{\text{m}}$.

Since a shipping cask must maintain its integrity under dynamic loading conditions, the pertinent material property is fracture toughness under dynamic loading conditions. Several studies have been made on the static fracture toughness properties of nodular cast iron. However, information on dynamic fracture toughness of thick section nodular cast iron is almost nonexistent.

4.0 APPLICATION OF FRACTURE MECHANICS TO SHIPPING CASKS

Crack growth leading to a through-wall flaw in a shipping container must be prevented. Unstable crack propagation resulting from stresses imposed under some hypothetical accident condition is the likely scenario for such crack growth. This failure scenario assumes that flaw sizes inherent to an as-fabricated containment system are sufficiently large, and that these flaws are not readily detectable by conventional non-destructive inspection techniques. This inspection precludes the existence of a crack of sufficient length which could initiate and propagate in a brittle manner under hypothetical accident loading. In-service stable crack growth of a smaller defect to some larger size by some mechanism such as fatigue under normal operating conditions has been shown to be extremely unlikely/9/.

A linear-elastic fracture mechanics (LEFM) design approach can be adopted to ensure no unstable crack initiation in a containment system under loads as high as those associated with even the most severe hypothetical accident condition. To apply a LEFM analysis, information must be available regarding fundamentally related

parameters: applied stress, flaw size, and the cask material's fracture toughness. Knowing any two of these parameters allows prediction of the third critical parameter.

For the present application, the applied stress is the maximum stress to which the shipping container may be subjected as a result of the most severe hypothetical accident condition. This stress potentially serves to define the critical failure stress. Regardless of the failure prevention methodology adopted, the true applied stresses during an accident event are fixed; only an otherwise arbitrary definition of this value for a particular failure prevention approach makes this term a variable (such as mandating that a stress equivalent to the material's yield strength be assumed).

The critical flaw size, a_c , for the unstable crack initiation is, of course, a function of the applied stress and fracture toughness. From the maximum applied stress, the maximum tolerable flaw size may be calculated for a cask of a given fracture toughness. Alternatively, the maximum allowable flaw size for an in-service container may also be fixed depending on the reliability of non-destructive inspection techniques.

The fracture toughness is defined by testing the containment cask materials according to prescribed ASTM E399 test techniques. Fracture toughness may also be derived from a 'reference toughness' correlation with some other less fundamental test such as the Charpy V-notch energy or the nil-ductility transition temperature. Such correlations facilitate quality control programs, but must be based upon a suitable data base for a particular material and for the particular loading rate and temperature of interest, and may be prohibitively conservative.

5.0 FRACTURE EVALUATION

5.1 Defect Model

It is assumed that the cask is protected at both ends by an impact limiter and that the drop orientation which would inflict maximum damage would be a side drop onto the impact limiter. In such a case, the maximum stress would occur at the outer surface of the mid-span location. Typical defects in cast iron would be gas porosity, shrinkage cavities and retained carbide. These defects all have finite size in three dimensions and normally tend to be located away from the surface of the casting. In this analysis, these defects were modelled conservatively as a circumferential surface flaw as shown in Figure 5.

5.2 Material

The cask is assumed to be constructed of nodular cast iron similar to that specified as GGG-40 in the German standard DIN-1693. The nodular cast iron has a static fracture toughness of approximately 60 MPa $\sqrt{m}$ (54 ksi $\sqrt{in}$) and a yield strength of approximately 276 MPa (40 ksi).

5.3 Stress

A finite element analysis simulating a nine-meter drop test is required to determine the maximum stress in a shipping cask. The D&D Report No. 83277/10/ contains a dynamic finite element analysis of a two module stainless steel shipping cask protected by only one impact limiter. Therefore, these results cannot be applied directly to a cast iron storage/transportation cask. Reference/9/ contains dynamic stress analysis results of a similar sized nodular cast iron cask as a function of the compliance of the impact limiters. The maximum stress occurred at the outer surface of the mid-span location and ranged from 42 to 126 MPa (6.1 to 18.3 ksi). The stresses were well below the cask material's yield strength.

5.4 Applied Stress Intensity Factors

The stress intensity factor, K at the tip of a semi-elliptical crack of maximum depth a is given by:

$$K = 1.12 S \sqrt{\pi a/Q} \quad (1)$$

where S = applied stress

a = crack depth

Q = shape factor = $\sqrt{\Phi^2 - 0.212 S^2/S_y^2}$

in which $\Phi = \frac{3\pi}{8} + \frac{\pi}{8} \frac{a^2}{c^2}$

S_y = yield strength

c = crack length on the surface

Equation (1) was plotted to calculate the critical crack depth for the following combinations.

- i. applied stress: 100 MPa, 150 MPa, 200 MPa, 250 MPa, 276 MPa
- ii. aspect ratio (a/c): 1/1, 1/2, 1/3, 1/6
- iii. yield stress: 276 MPa

Computed K values for crack depths up to 200 mm are shown in Figure 6-10 at various stress levels. Figure 11 summarizes the K vs a curves for an aspect ratio of 1/3.

Results from an embedded crack model are also included in Figure 8, and show that a surface crack model assumed in this analysis is conservative in comparison to an embedded crack model.

5.5 Critical Crack Depth

Critical crack depths (ccd) corresponding to a given fracture toughness value of $60 \text{ MPa}\sqrt{\text{m}}$ were calculated and are listed in Table 3.

TABLE 3 PREDICTED CRITICAL CRACK DEPTH FOR $K_{IC}=60 \text{ MPa}\sqrt{\text{m}}$

Applied Stress	Aspect Ratio (a/c)			
	1/1	1/2	1/3	1/6
100 MPa	143 mm	115 mm	111 mm	107 mm
150 MPa	62 mm	50 mm	47 mm	46 mm
200 MPa	35 mm	28 mm	27 mm	26 mm
250 MPa	23 mm	18 mm	17 mm	17 mm
276 MPa	18 mm	14 mm	13 mm	13 mm

Typically a 10 mm crack can be easily detectable by a conventional NDE technique. Therefore, above values are well above the detectability limit of NDE that exists in the cask.

These ccd values are conservative because:

- i. The applied stress used was from the nine-meter drop with an orientation which will inflict maximum damage.
- ii. The K calculation equation is for a two-dimensional crack including the effect of crack front curvature.
- iii. A lower bound plane strain fracture toughness (K_{IC}) for the cask material was assumed.

5.6 Minimum Fracture Toughness

Figure 11 can be utilized to determine the minimum fracture toughness corresponding to various ccd values, which are given in Table 4.

TABLE 4 REQUIRED MINIMUM FRACTURE TOUGHNESS

Applied Stress	Critical Crack Depth		
	5 mm	10 mm	20 mm
100 MPa	13 MPa $\sqrt{\text{m}}$	17 MPa $\sqrt{\text{m}}$	25 MPa $\sqrt{\text{m}}$
150 MPa	19 MPa $\sqrt{\text{m}}$	26 MPa $\sqrt{\text{m}}$	39 MPa $\sqrt{\text{m}}$
200 MPa	26 MPa $\sqrt{\text{m}}$	37 MPa $\sqrt{\text{m}}$	51 MPa $\sqrt{\text{m}}$
250 MPa	34 MPa $\sqrt{\text{m}}$	46 MPa $\sqrt{\text{m}}$	66 MPa $\sqrt{\text{m}}$
276 MPa	35 MPa $\sqrt{\text{m}}$	50 MPa $\sqrt{\text{m}}$	70 MPa $\sqrt{\text{m}}$

6.0 CONCLUSIONS

Material properties and design criteria which are relevant to the fracture prevention of nodular cast iron shipping containers were reviewed and a series of LEFM analyses were performed to assess the margin of safety inherent to a proposed cask design.

It was demonstrated through a LEFM procedure that the NMMD's proposed shipping cask design, of nodular cast iron, can withstand a nine-meter drop. No crack initiation would occur even if a flaw of a size well above the detection limit of conventional NDE exist in the cask. The fracture toughness of nodular cast iron is sufficient to ensure the structural integrity of these casks.

7.0 RECOMMENDATIONS

Based on a literature survey and a preliminary LEFM analyses, it is concluded that it is feasible to construct spent fuel shipping containers of nodular cast iron material. The following recommendations are a proposed route to qualify nodular cast iron containers for Canadian use.

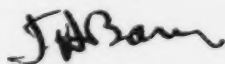
1. A concentrated effort should be made to gather pertinent information regarding material specification and acceptance criteria for thick section cast iron casks which have been developed in West Germany.
2. An acceptance criteria for cast iron casks for Canadian use should be established and submitted to AECB for approval.
3. The lowest operating temperature for cast iron casks should be established, keeping in mind that it would be cheaper to qualify a container for -20°C than for -40°C .

4. A preliminary test program should be conducted using separately cast thick section cast iron blocks to determine whether the specified static and dynamic fracture toughness values are met.
5. Conduct a stress analysis of cast iron casks to determine the service stresses under hypothetical accident conditions.
6. Establish the lower bound 'ASTM valid' dynamic fracture toughness values as a function of temperature from materials taken from actual casks.
7. Establish a correlation between the actual cask material and the separately cast test blocks for quality control purposes.
8. Establish inspection limits.
9. Conduct drop tests using unflawed casks.

The recommendations given in 10 to 13 apply if the option to conduct drop tests using casks with artificially introduced flaws is adopted.

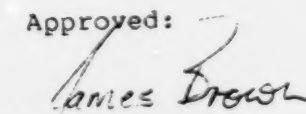
10. Choose the size of an artificial flaw. Conduct a drop test using casks with artificially introduced flaws at the maximum primary and secondary stress locations.
11. Conduct pre-cracked Charpy tests to determine the minimum dynamic fracture toughness in the vicinity of the experimental crack and the minimum toughness in other parts of the cask.
12. Establish a correlation between an actual cask and a test block for quality control purposes.
13. Establish inspection limits.

Recommended:



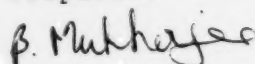
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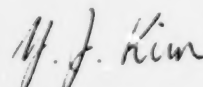


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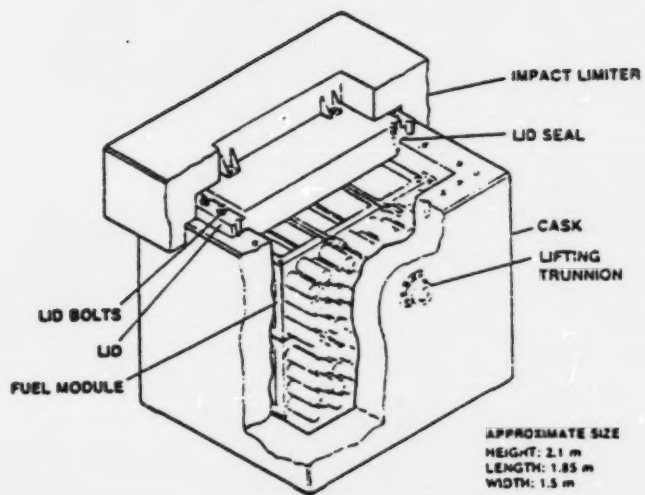
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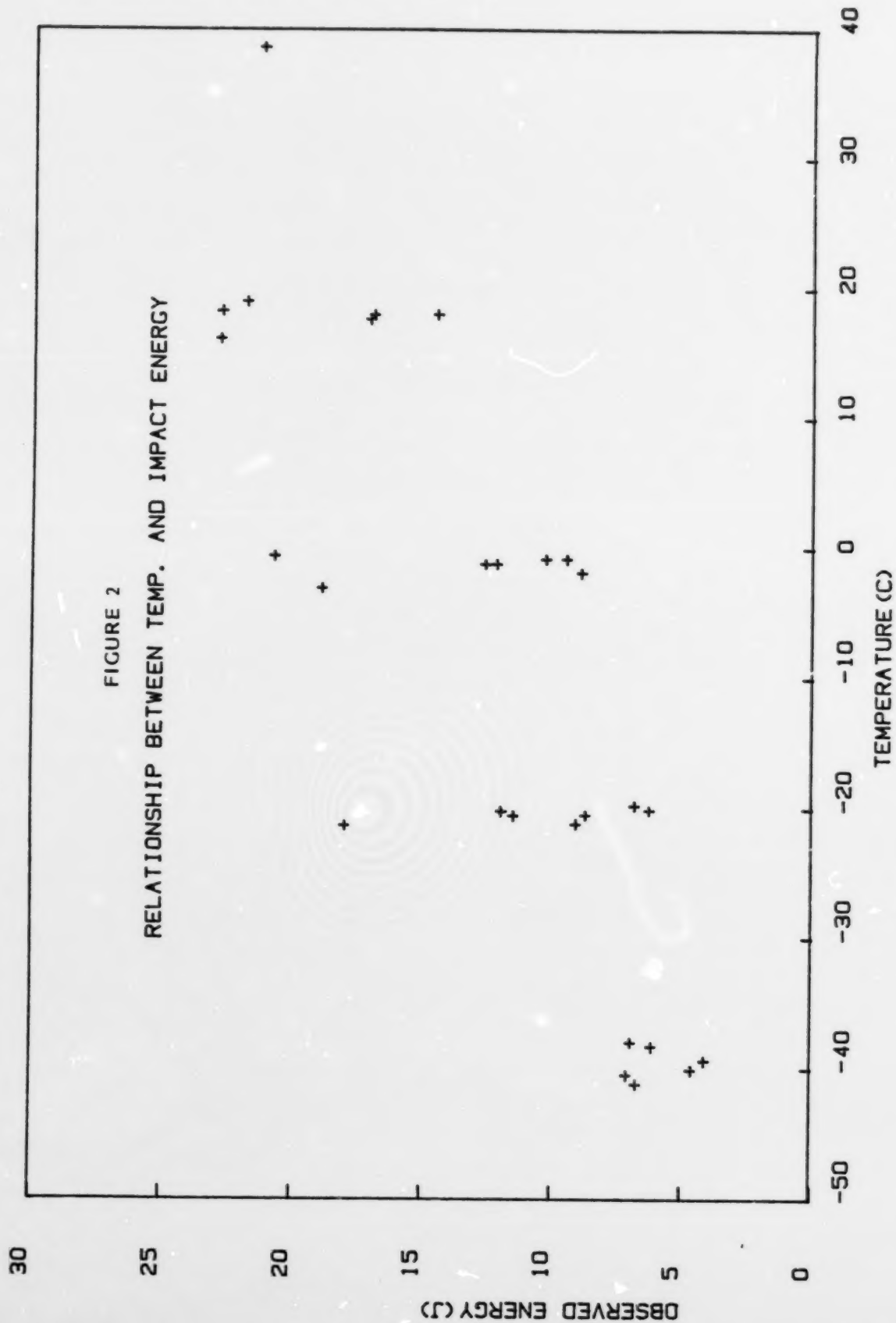
REFERENCES

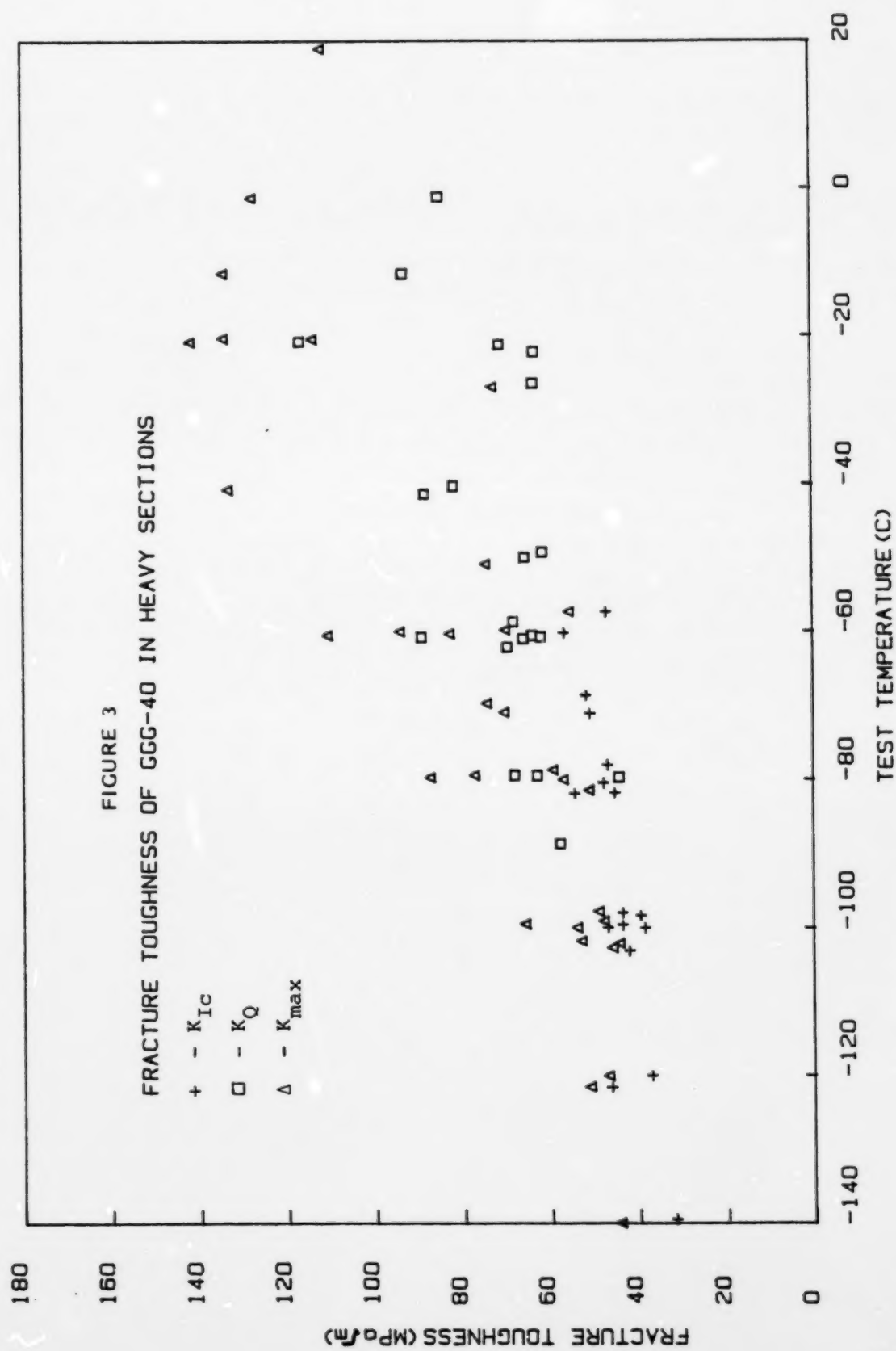
1. Rollins, J. "Properties of Nodular Ductile Graphite Cast Iron Used in GNS Manufactured Spent Fuel Casks", Patram 83., pp. 119-125.
2. Keese, H. and Anspach, W. "The TN 1300 Transportation/Storage System", PATRAM 83, pp 242-247.
3. Anspach, W. and Wolters, D. "TN 1300 Casting Process and Material Qualification", PATRAM 83, pp 126-131.
4. Nucleonics Week, Vol 25, No. 18, May 3, 1984.
5. K.E. Nash, "Feasibility of Using Cast Iron In Irradiated Fuel Management", IFTU Memorandum #061, May 1984.
6. Schwartz, M.W. and Boyce, L. "Ductile and Brittle Design Criteria for Nodular Cast Iron Spent-Fuel Shipping Containers", UCRL-53046, Lawrence Livermore Laboratory, March 1983.
7. Schwartz, M.W., "Recommendations for Ductile and Brittle Failure Design Criteria for Ductile Cast Iron Spent-Fuel Shipping Containers", NUREG/CR-3760, UCRL-53532, Lawrence Livermore National Laboratory, April 1984.
8. Motz, J.M., "Fracture Mechanics Properties in Heavy Section of Nodular Iron Castings", Giesserei 67 (1980), NR 20-29, pp 628-637.
9. McConnell, P., Wullaert, R.A. and Trujillo, A., "Application of Linear-Elastic Fracture Mechanics Concepts to Ferritic Spent Fuel Shipping Casks".
10. Sauve, R.G. and Fogarthy, J.P. "Preliminary Analytical Assessment of the Irradiated Fuel Transportation Cask Concepts - Dynamic Impact Simulation", Ontario Hydro D&D Report No 83277.

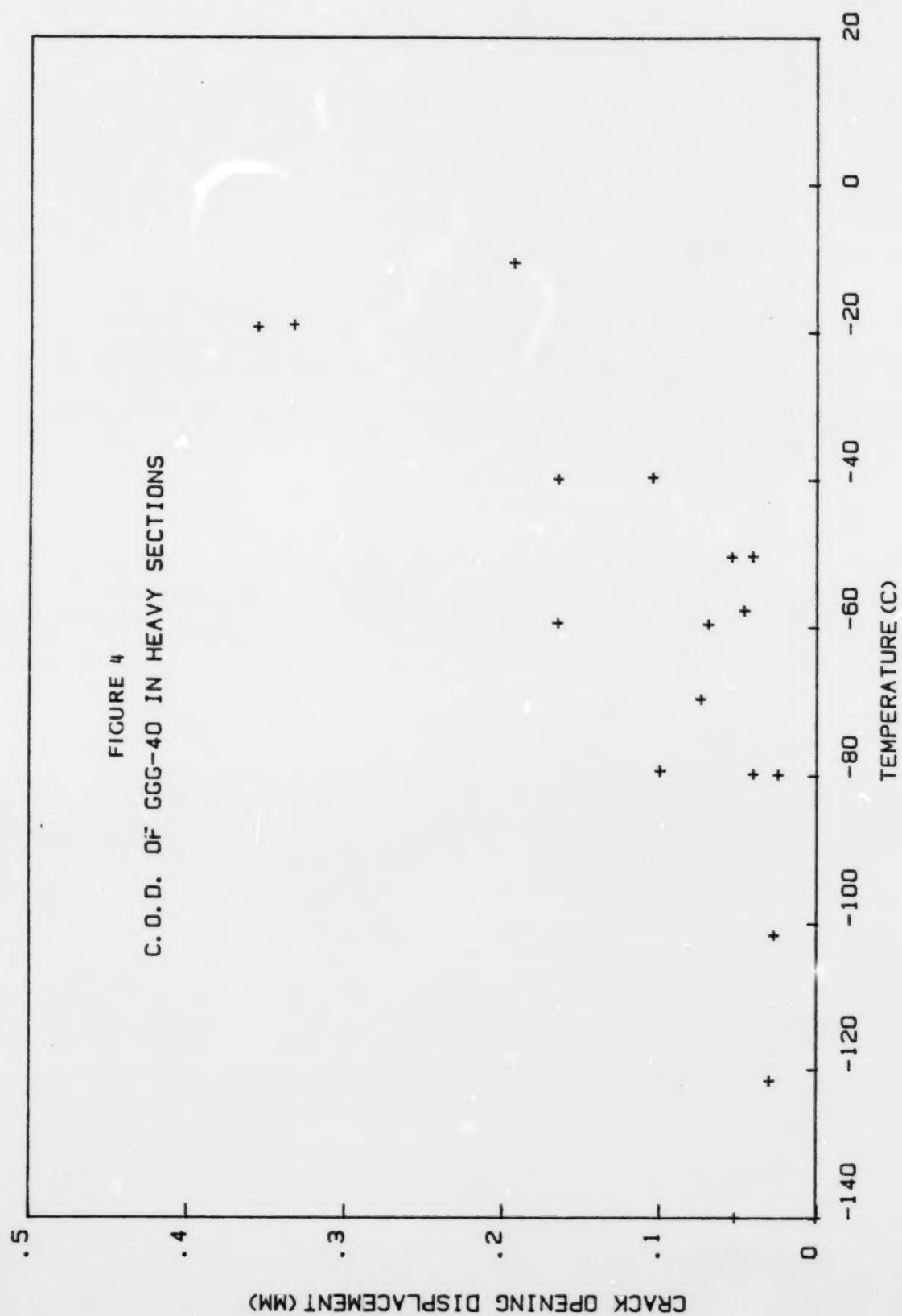


CANDU Irradiated Fuel Road Cask

FIGURE 1
CANDU IRRADIATED FUEL ROAD CASK /10/







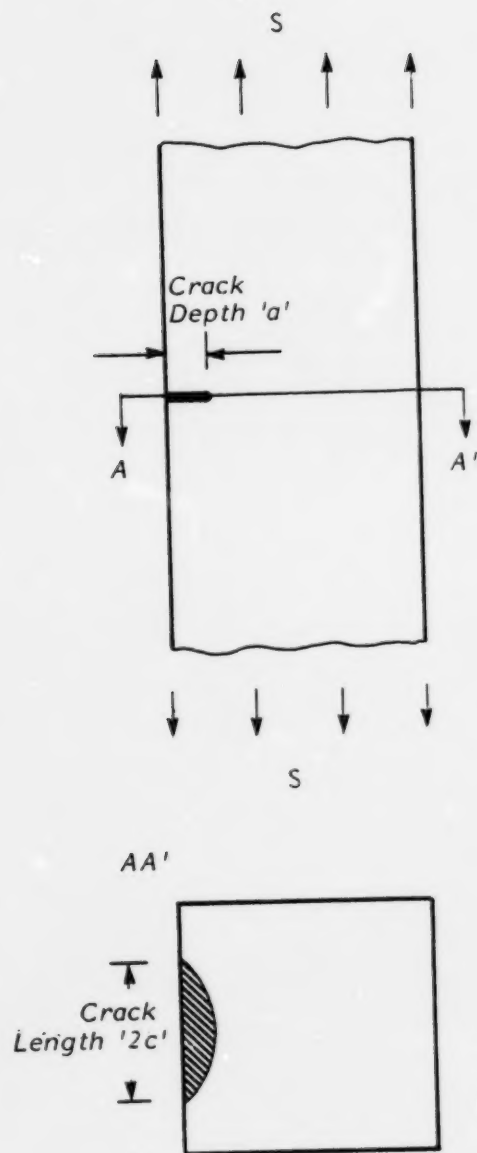


FIGURE 5
FLAW EVALUATION MODEL

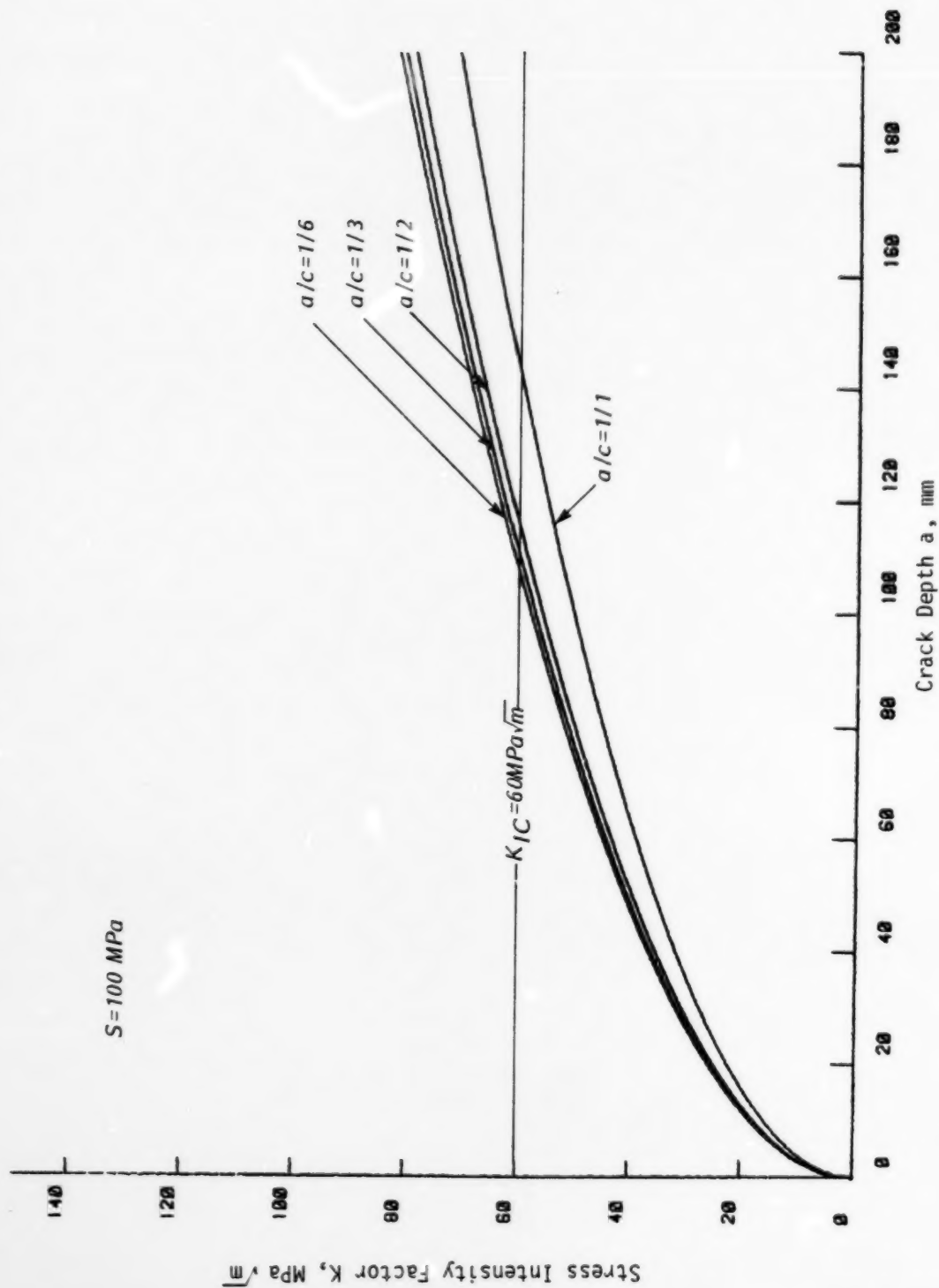


FIGURE 6
STRESS INTENSITY VS CRACK DEPTH: 100 MPa

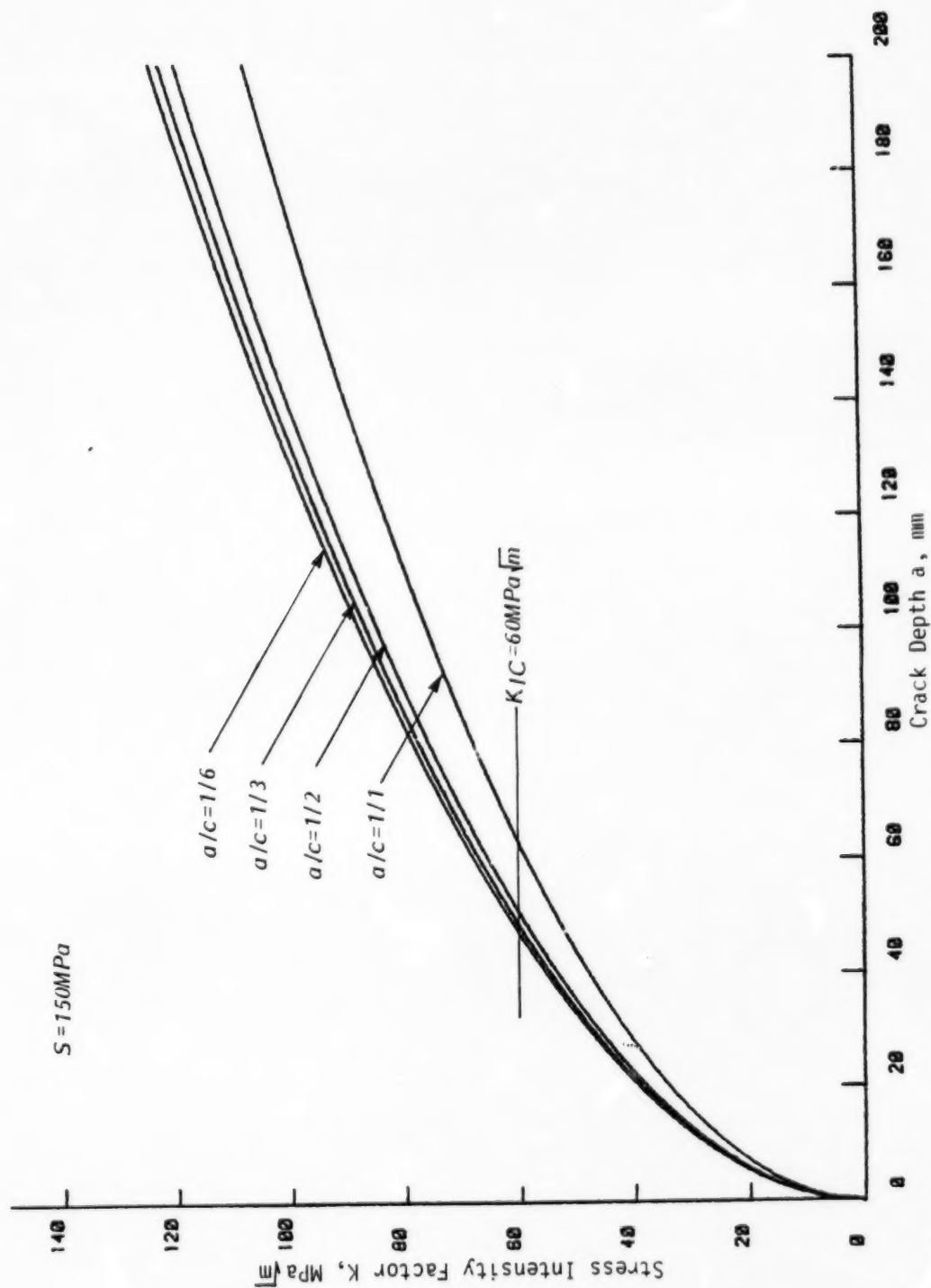


FIGURE 7
STRESS INTENSITY VS CRACK DEPTH: 150 MPa

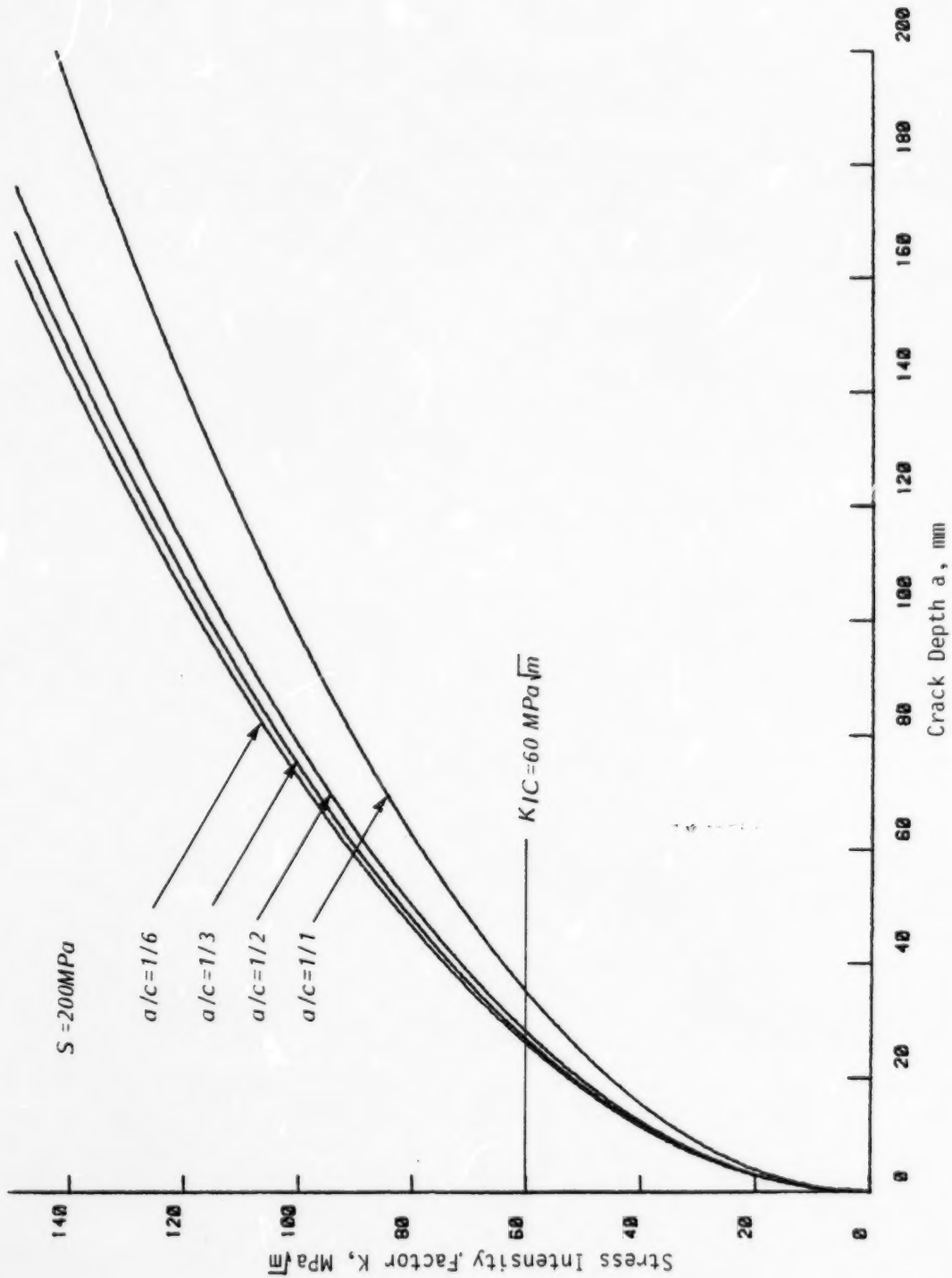


FIGURE 8
STRESS INTENSITY VS CRACK DEPTH: 200 MPa

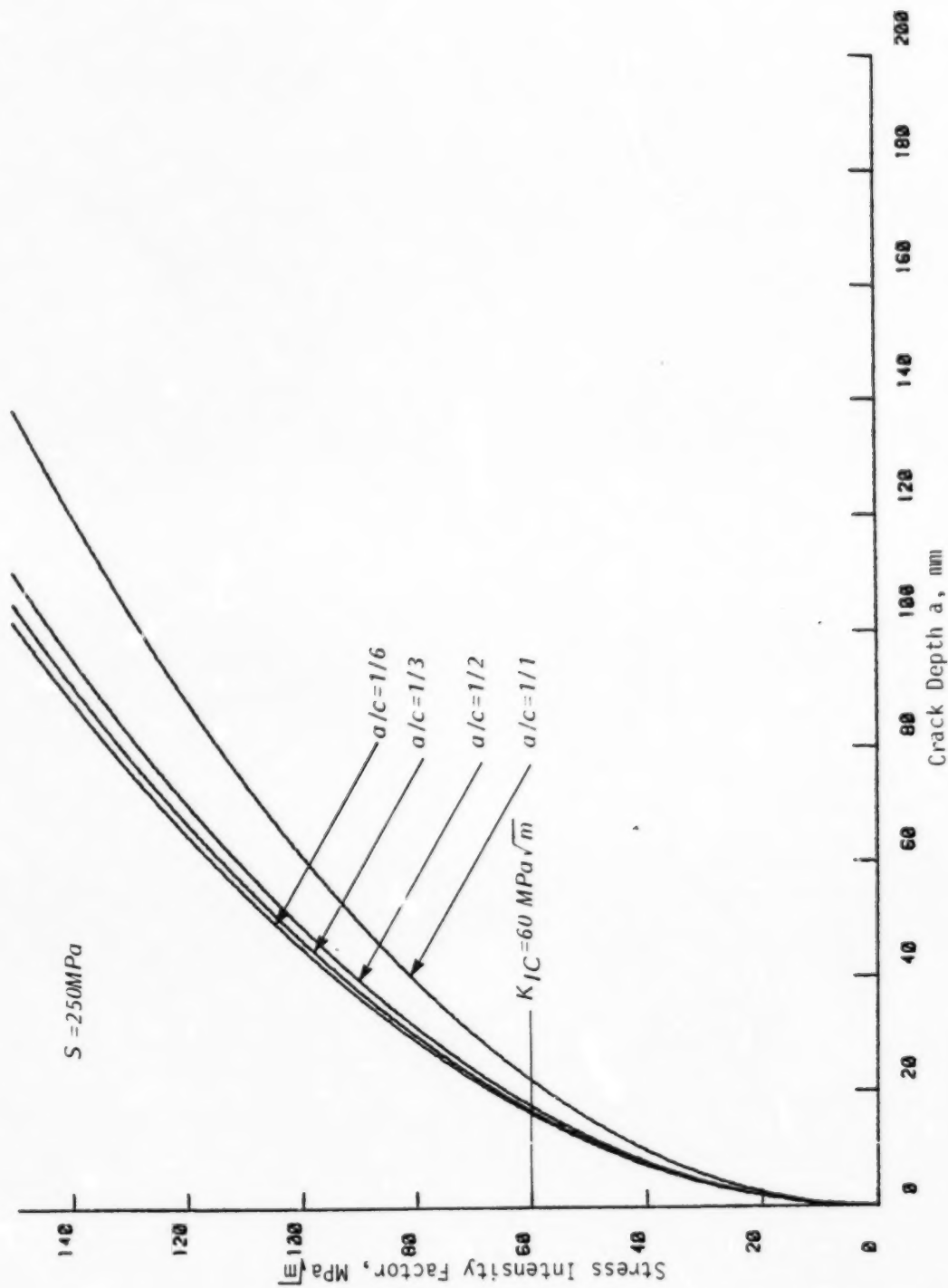


FIGURE 9
STRESS INTENSITY VS CRACK DEPTH: 250 MPa

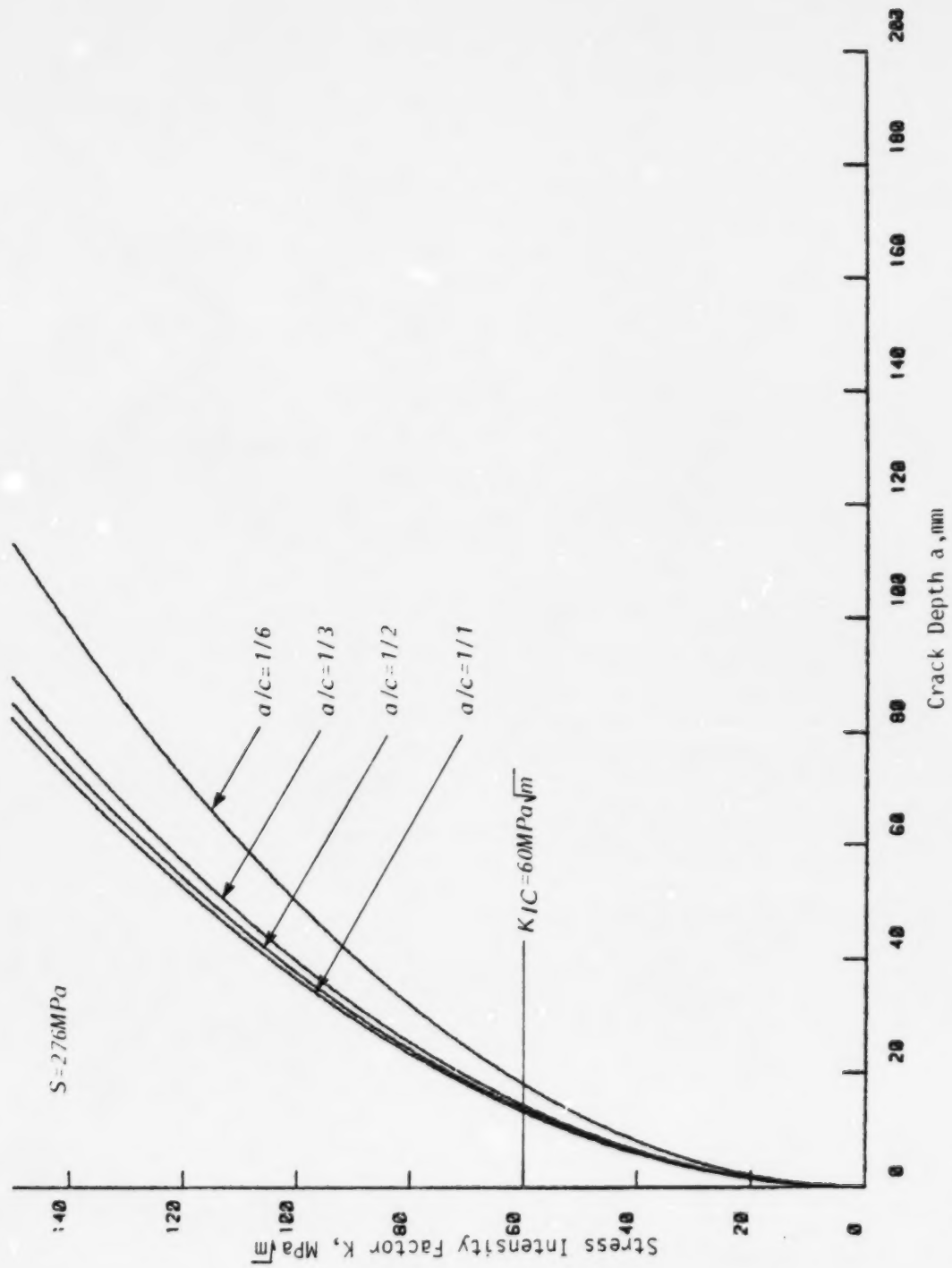


FIGURE 10
STRESS INTENSITY VS CRACK DEPTH: 276 MPa

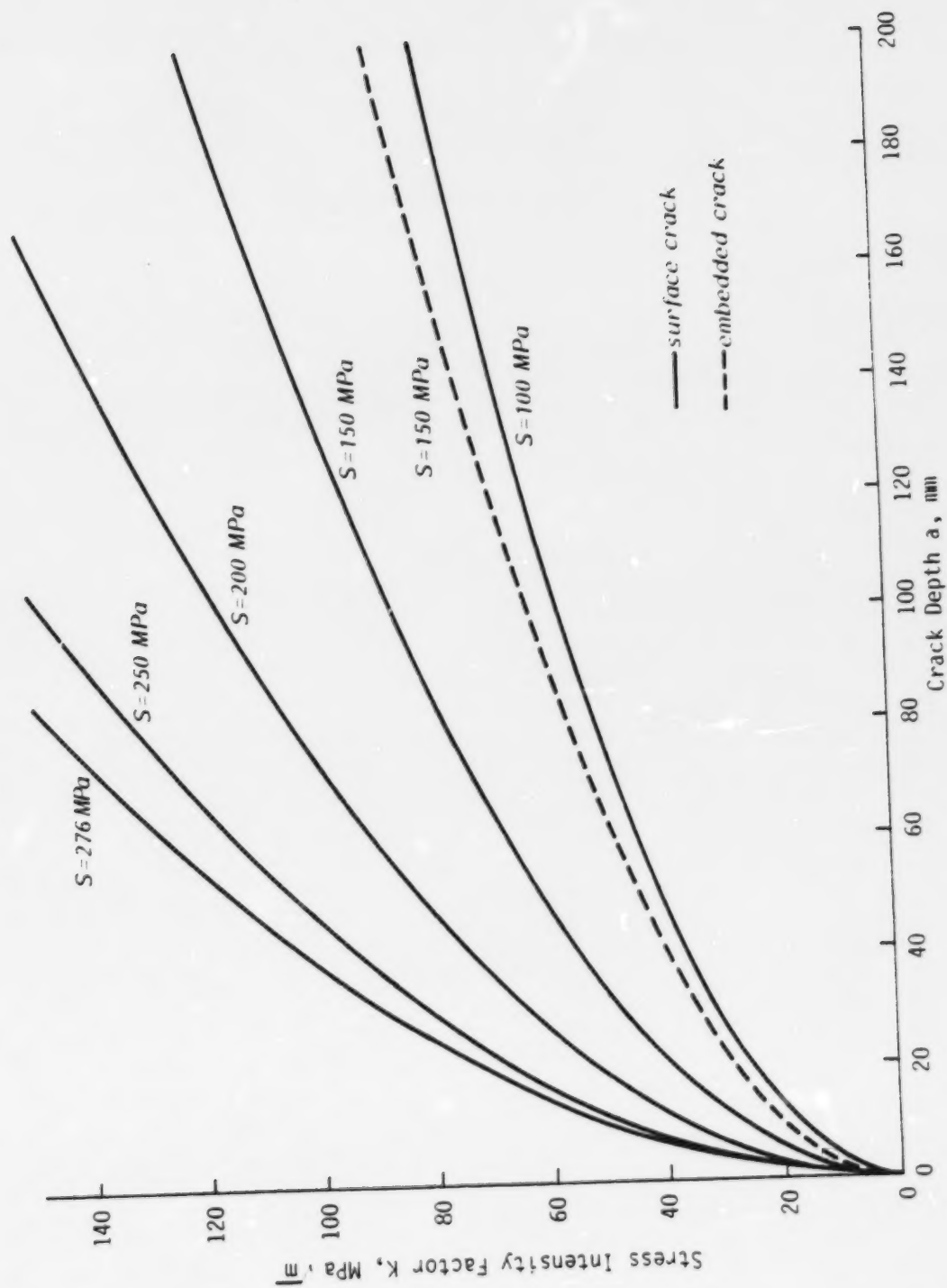


FIGURE 11
STRESS INTENSITY VS CRACK DEPTH: SUMMARY